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Paper Title:

Splitting Failures in Trapezoidal Steel Roof Cladding

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ABSTRACT

High wind events such as hurricanes and storms often cause severe damage to crest-fixed thin steel roof claddings. Past research on wind damage has shown that low cycle fatigue cracking of steel roof sheeting around the fastener holes has been the reason for the premature pull-through failures of roof claddings under fluctuating wind forces. Such a situation will be at its worst if the roof sheeting is already split at the fastener holes. An inspection of trapezoidal steel roofs has shown that roofing has been split in the transverse direction due to accidental or poor workmanship-caused overtightening of screw fasteners. Once split, even slightly, the roofing can only survive a few cycles of wind uplift loading. Therefore an investigation using laboratory experiments and finite element analyses was carried out to study the splitting behaviour of two commonly used high tensile steel trapezoidal roof claddings. Analytical and experimental results agreed reasonably well and presented a good understanding of the splitting behaviour of trapezoidal roof claddings. This paper presents the details of this investigation and the results.

Keywords

Splitting failures, Trapezoidal steel roof cladding, Wind loading, Experiments, Finite element analyses

INTRODUCTION

Light gauge steel roof claddings suffer severe damage during high wind events such as hurricanes and storms. This leads to the damage of the entire building and its contents. In Australia and neighbouring countries, steel roof claddings are usually made of thin high strength steel with lower ductility (0.42 mm base metal thickness and G550 steel with a minimum guaranteed yield strength of 550 MPa) and are crest-fixed with self-drilling screw fasteners. They are subjected to large uplift pressures during high winds that cause localised stress concentrations around the fastener holes. The presence of these large stress concentrations in the thin steel sheeting around the fastener hole causes low cycle fatigue cracking of sheeting when the cladding is subjected to randomly fluctuating wind forces during hurricanes or storms (Beck and Stevens, 1979, Mahendran, 1990, 1994a). This leads to a premature pull-through failure (Figure 1) that is commonly observed during cyclic tests of roof sheeting and investigations following severe wind events. The resulting disengagement of roof cladding causes extensive damage to buildings and their contents (Mahendran, 1995). Such a situation will be at its worst if the roof sheeting is already split under the screw head.

An inspection of steel roofs made of trapezoidal steel sheeting (Reardon and Mahendran, 1988) has shown that roofing has been split in the transverse direction under the screw heads due to the overtightening of screw fasteners either accidentally or by poor workmanship (see Figure 2). The transverse splitting was observed in more than ten locations on the roof, that is, at more than 50% of the locations inspected. The splitting mode was identical and included permanent dimpling of the crest within the rib and transverse splitting as shown in Figure 2. Once split, even slightly, the roofing can only survive a few cycles of uplift wind loading. Fatigue cracking will propagate rapidly around the fastener holes at lower wind uplift loads and let the screw head pull through the steel roof sheeting. Constant amplitude cyclic tests on steel roofing specimens that were slightly split due to accidental overtightening have confirmed the above occurrence (Mahendran, 1994a). The number of cycles to failure was unusually low compared with that for roof sheeting without any transverse splits. During hurricanes and storms, the loss of a few roof sheets often leads to a rapid loss of the entire roof. This demonstrates the importance of avoiding the presence of even a few transverse splits. Therefore an investigation using laboratory experiments and finite element analyses was carried out to study the splitting behaviour of two commonly used trapezoidal roof claddings (BHP, 1990), which were made of 0.42 mm G550 high tensile steel (see Figure 3). Thermal movement in steel roofing may worsen the initial transverse splits. However, since its effect is considered smaller than that of cyclic wind uplift forces, it was not considered in this investigation.

This paper presents the details of the analytical and experimental methods and the small scale roofing models used in studying the splitting behaviour of trapezoidal roofing and the results. It then discusses the reasons for the splitting behaviour, and makes useful recommendations.

EXPERIMENTAL INVESTIGATION

In order to study the splitting mechanism in detail, a series of laboratory experiments was conducted using a two-span roofing model. Initially, trapezoidal-Type A sheeting was used in the experiments. A specially made screw fastener that was long enough to accommodate a small load cell within its length was used in this model. The type of self-drilling screw fasteners used in the roofing industry (HiTeks or Type 17) depends on whether the supporting members (purlin/batten) are steel or timber (see Figure 3(c)). They usually include a neoprene washer under the screw head. The screw head and shaft sizes used in the model were the same as those of the commonly used No.14-10 self-drilling screw fastener, that is 14.5 mm and 5.2 mm, respectively (ITW, 1995). The location of this screw fastener was changed within the two-span roofing model for each test (see Table 1). The screw fastener was then tensioned using a simple hand-tightening method (shown later in Figure 6(c)) to simulate the overtightening that could occur in practice and that leads to permanent dimpling of crests and transverse splitting. This was continued until the splitting occurred as shown in Figure 2 and the splitting load was noted in each test. The use of a simple hand tightening method was considered adequate as the main aim of this experimental investigation was to simulate the dimpling of the crests and transverse splitting of steel sheeting caused by overtightening. Following the two-span model tests, the same tests were also conducted on roofing models with only one support. Figure 4 shows one of the large scale roofing models used in the tests. Table 1 presents the results of these experiments.

As seen from the results in Table 1, the splitting load ranged from 1475 to 1575 N and the type of splitting was identical for the 650 mm wide two-span models and the 750 mm wide models with only one support. This indicates that the splitting phenomenon does not depend on the fastener location and is essentially a localised effect. Figure 5 shows the deformed sheeting caused by the overtightening of the screw fastener. The process leading to splitting can be described as follows:

- Localised dimpling of crest occurs in the vertical direction and is associated with spreading of rib caused by the slip occurring at points A and B in the horizontal direction along the purlin/batten. The amount of slip depends on the friction between the sheeting and purlin/batten. The slip also leads to global vertical deflection of the entire rib.

- When the local dimpling displacement, Δ (see Figure 5), has reached about 4 to 5 mm, the splitting occurs in the transverse direction at the screw fastener hole. When the slip is reduced by greater friction between the sheeting and purlin/batten, this critical local dimpling displacement of 4 to 5 mm is reached sooner, but splitting occurs at the same load.

When narrow strips of sheeting were used in the test model, the lateral slip occurred freely at points A and B and hence no splitting occurred. Therefore these models were considered inadequate to study the splitting behaviour.

The influence of overtightening of screw fasteners on the sheeting was very localised and extended only about 100 mm on either side of the fastener hole in the longitudinal direction (see Figure 2). Hence the length of roofing model beyond 200 mm did not affect the splitting load results. Considering all these observations, it was therefore decided to use a small scale roofing model shown in Figure 6 to investigate the splitting behaviour further. This model including a single trapezoidal rib was only 200 mm long as it has already been shown that dimpling is localised within 200 mm length and that there is no need to include longer sheets. A screw fastener was added to the model at points A and B to eliminate the slip at these points and thus to simulate the lateral continuity of the sheeting. The lateral continuity of the sheeting in practice allows some slip at points A and B, but the splitting load did not depend on the slip. It was essentially dependent on the local dimpling deflection (Δ, see Figure 5). The slip at points A and B was translated to simple elastic global deflections of the entire rib, and hence did not affect the splitting load. This small scale model shown in Figure 6 was therefore adopted and a number of tests were conducted to prove its adequacy (see Table 1).

These results (1538 N/f) agreed well with the large scale test results (1518 N/f) as shown in Table 1 for trapezoidal-Type A sheeting and thus validated the use of the small scale roofing models in studying the splitting behaviour of steel roof sheeting caused by overtightening. The use of small scale roofing models in this manner simplifies the test procedure and enables large number of tests to be undertaken with reduced time and resources. It must be noted that local dimpling displacement (Δ) was about the same (about 4 to 5 mm) in all experiments.

The small scale models are very easy to use and provide a faster and efficient method of determining the splitting load. Therefore they were then used for trapezoidal-Type B sheeting. The splitting behaviour was very similar to that of Type A sheeting, and the splitting loads are given in Table 1 (average load = 1465 N/f).

Some tests were conducted on another commonly used roof sheeting, the arc-and-tangent corrugated roofing. In this case, splitting did not occur as the reduced friction between the curved sheeting and purlins/battens allowed unrestrained spreading of the sheeting leading to almost flattening of the sheeting, but splitting did not occur.

FINITE ELEMENT ANALYSIS

In order to study the splitting behaviour of trapezoidal steel roof sheeting, finite element analyses (FEA) were also conducted. Experimental investigation has demonstrated that a small scale roofing model shown in Figure 6 can be used to study the splitting at the fastener holes. The use of two-span roofing models is unnecessary for this study. Therefore, the small scale roofing model used in the experiments was analysed using a finite element program ABAQUS (HKS, 1997). Four-noded quadrilateral shell elements were used to model the thin steel sheeting. A quarter model was considered adequate because of symmetric loading, geometry and support conditions. A suitable mesh density was chosen based on a convergence study, and is shown in the finite element model in Figure 7. Three-dimensional eight noded continuum hybrid elements were used to model the hyperelastic behaviour of 2 mm neoprene washer located between the screw head and steel sheeting. Hybrid elements are used when the material behaviour is incompressible, as incompressible material behaviour cannot be modelled using regular elements. A convenient way of defining a hyperelastic material is to provide ABAQUS with experimental test data. ABAQUS then calculates the required material constants using the least squares method. Experimental test data from uniaxial compression tests of neoprene washers were used in this analysis (Tang and Mahendran, 1999). Three dimensional eight nodded continuum elements were used to model the screw head. Appropriate boundary conditions were used along the edges of the model based on the symmetry of the model and actual support conditions used in the experiments. Constraint conditions between steel sheeting, neoprene washer and screw head must be modelled adequately. For this purpose, master slave contact pair option was used. Contact surfaces between steel sheet, neoprene washer and screw head were modelled as tied contact. The tied contact bonds the contact surfaces to each other, thus eliminating severe discontinuities. In this simulation, the washers were selected as slave surfaces with finer mesh since they are softer than others. A uniformly distributed load was applied to the screw head to simulate the load distribution caused by overtightening through the neoprene washer under the screw head. A non-linear ultimate strength analysis including both material and geometry effects was conducted. Following material properties of steel were used in the analyses: modulus of elasticity E = 200,000 MPa and Poisson's ratio ν = 0.3 (assumed) and yield stress = 690 MPa (measured).

RESULTS AND DISCUSSION

The load-deflection results obtained from the FEA are compared with the corresponding experimental results in Figure 8 for trapezoidal-Type A roof sheeting. The same procedure was used for trapezoidal-Type B sheeting and the results are given in Figure 9. Note that the deflection in these curves was the vertical deflection at the fastener hole (see Figure 5). Experimental and FEA deformation shapes agreed reasonably well as shown in Figures 2 and 7(b), respectively. The load-deflection curves also agreed reasonably well for both Types A and B sheeting as seen in Figures 8 and 9. The ultimate loads agreed well while the difference between the deflections from FEA and experiments is within 1 mm at any load level. Experimental deflections were larger than the FEA deflections as the FEA model could not model all the experimental conditions such as the possible slip between the sheeting and timber purlin at the screw fastener (see Figure 6). It must be noted that the FEA does not include a criterion for splitting. Hence the failure load predicted by the FEA may not relate to splitting in all cases although the failure loads agreed well here (see Figures 8 and 9). However, as indicated by past research (Mahendran, 1994b), the transverse splitting occurs due to complicated large deformations around the fastener hole and is likely to occur at or near the peak loads predicted by the FEA. Despite some shortcomings of the FEA model, as described above, it produced adequate results for this paper aimed at improving the understanding of splitting behaviour beyond the experimental and field observations.

In order to understand the reasons for splitting, the strain readings obtained from the experiments and FEA were analysed. It was found that as the screwed crest deformed, the longitudinal membrane tensile strains at the transverse edge of the screw fastener hole increased rapidly and were considerably high at the splitting load. Figure 10 shows the longitudinal membrane strain contours for the sheeting around the fastener hole. In fact, the maximum longitudinal membrane tensile strains at the edge of the hole were approaching the failure strain values of 0.02, measured in the tensile coupon tests of the less ductile G550 steel used in this study. Based on these strains, the following reasons are considered to cause the splitting observed in the trapezoidal sheeting. Recent research aimed at determining the reasons for splitting in G550 steel claddings (Mahaarachchi and Mahendran, 2000) has shown that transverse splitting occurs when

- the longitudinal membrane tensile strain is greater than 60% of the total tensile strain at the edge of the fastener holes and
- the total tensile strain is equal to the measured failure strain from tensile coupon tests of steel.

Overtightening of trapezoidal steel roof sheeting develops large membrane tensile strains in the longitudinal direction and high total strains around the fastener hole and hence meets the abovementioned splitting criterion. This therefore initiates the transverse splitting at the edge of the screw fastener hole.

To validate the above explanation, a small scale trapezoidal roofing model was made of a more ductile steel that had a strain at failure of about 0.2. In this case, a greater failure load was achieved with no splitting. The sheeting underwent large dimpling type deformations, but did not undergo splitting as shown in Figure 11.

Having determined the reason for the splitting behaviour of trapezoidal sheeting using both experiments and FEA, it is now necessary to consider ways of improving the splitting load. It must be noted that the static pull-through failure loads of the two trapezoidal claddings under wind uplift loading are 1450 and 1200 N/f (Mahendran, 1994b). Although the average loads causing splitting (1538 and 1465 N/f – see Table 1) were higher than the above loads, this experimental study showed that it was relatively easy to overtighten the screw fastener and to cause splitting. Therefore such splitting of trapezoidal sheeting observed in this study is likely to occur in practice and must be prevented to make the roof claddings safe during hurricanes and storms as even a minor splitting in the sheeting will lead to disengagement of the roof. The use of torque limited power tools can be considered to eliminate splitting in sheeting. However, it is unlikely as the same power tool is used to install the screw fasteners into the roof sheeting and the timber or steel batten in one operation. A higher torque will be required to install the screw fastener into the timber or steel batten than to install it through the thin steel sheeting. This means it is impossible to set a safe torque based on the splitting loads determined in this study to eliminate overtightening and associated transverse splitting of sheeting in practical installations. The following recommendations are made based on the results from this study and discussions above.

- When the commonly used trapezoidal steel roof claddings made of thin G550 steel are used, they must be installed by experienced builders to ensure no overtightening takes place. The initial crushing of neoprene washers can be used as an indicator in avoiding any overtightening of thin steel roof sheeting. The manufacturers’ roofing manuals must include advisory statements regarding this potential problem.

- As part of the design process, the manufacturers and designers of trapezoidal steel sheeting must use a small scale roofing model shown in Figure 6 to determine the splitting load and ensure that it is a reasonably high load that cannot be reached during the installation process. The splitting loads for the currently used trapezoidal profiles are rather low. The use of thicker roof sheeting and/or larger screw heads or washers will help to increase the splitting load.

- Modifying the geometry of trapezoidal sheeting using finite element analyses can eliminate the presence of large membrane tensile strains in the longitudinal direction. This will thus increase the splitting load (delay splitting).

- A more ductile steel with a strain at failure of at least 0.1 can be used to eliminate the transverse splitting failures in steel roof claddings.

CONCLUSIONS

This paper has described a detailed investigation into the splitting behaviour of two commonly used trapezoidal steel roof claddings. Both experimental and finite element analyses were used for this purpose. It was found that overtightening of screw fasteners led to splitting at the fastener holes when the slip between the sheeting and purlin/batten was not free to occur for these two trapezoidal claddings. Large longitudinal membrane tensile strains were present at the transverse edge of fastener holes and when these strains exceeded the limiting failure strain value of the high tensile steel used in the sheeting, the splitting of the sheeting occurred in the transverse direction. Experimental investigation led to the development of a suitable small scale roofing model that can be used by the manufacturers and designers in the design of trapezoidal steel roof claddings. A number of useful recommendations are also presented to eliminate the transverse splitting of roof sheeting caused by overtightening of screw fasteners.

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Table 1. Experimental Results

Roofing Model		Location of Overtightened Fastener	Splitting Load (N/f)	Average Splitting Load (N/f)*
Span (mm)	Dimensions (mm)			
Two-span	650 wide x 1400 long Trapezoidal Type A	Central support	1500	1518
Two-span	650 wide x 1400 long Trapezoidal Type A	End support with an overhang of 325 mm	1475, 1575	
Two-span	650 wide x 1400 long Trapezoidal Type A	End support with an overhang of 100 mm	1475, 1575	
Two-span	Narrow strip x 1400 long Trapezoidal Type A	Central and end supports	No splitting	
One support	750 wide x 1400 long Trapezoidal Type A	Support	1500	
One support	750 wide x 1200 long Trapezoidal Type A	Support	1540	
Small model	100 wide x 200 long Trapezoidal Type A	--------	1575, 1500	1538
Small model	100 wide x 200 long Trapezoidal Type B	--------	1440, 1490	1465

Note: * N/f = Newtons per Fastener

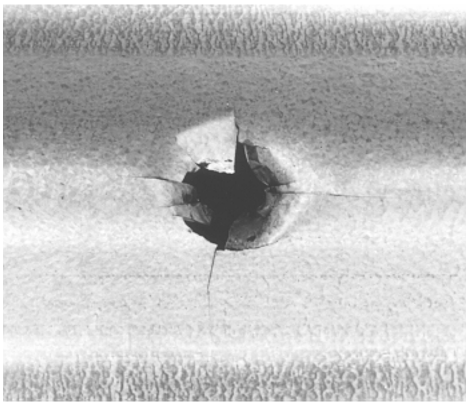


Figure 1. Fatigue Cracking of Steel Sheeting under Cyclic Wind Forces

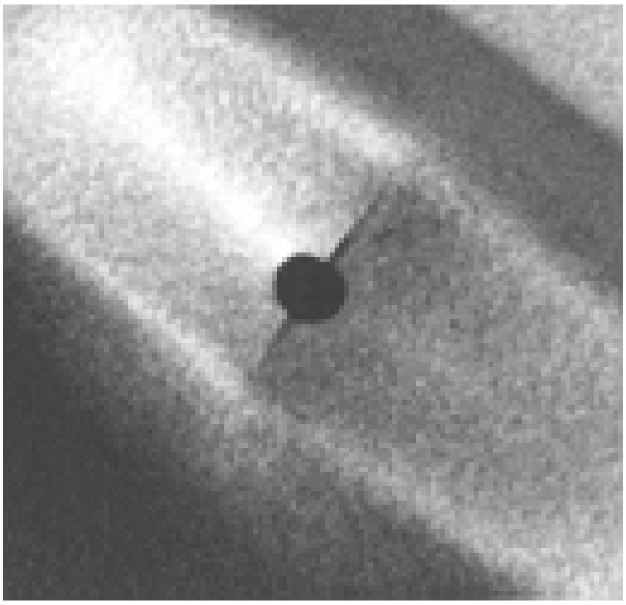
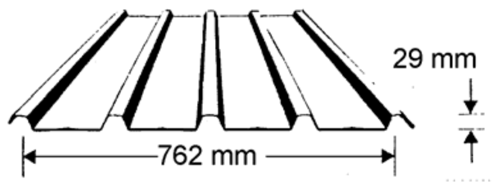
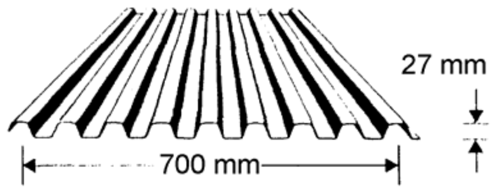


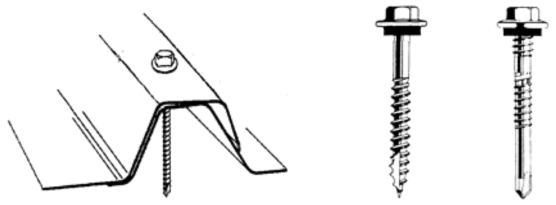
Figure 2. Split Trapezoidal Roof Cladding



(a) Type A



(b) Type B



Crest-fixing Type 17 HiTeks

(c) Crest-fixed Cladding with Self-drilling Screws

Figure 3. Trapezoidal Roof Cladding

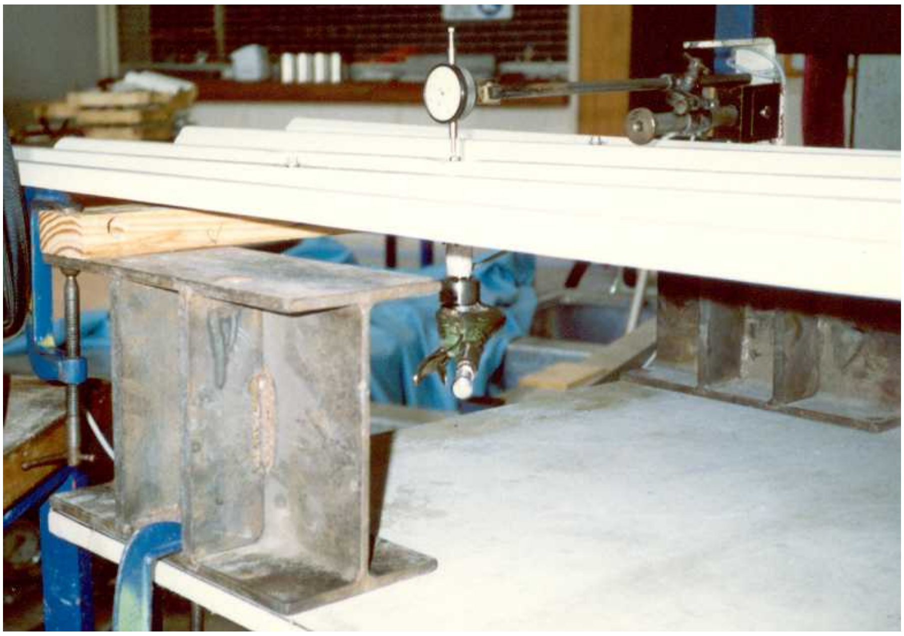


Figure 4. Large Scale Test Model

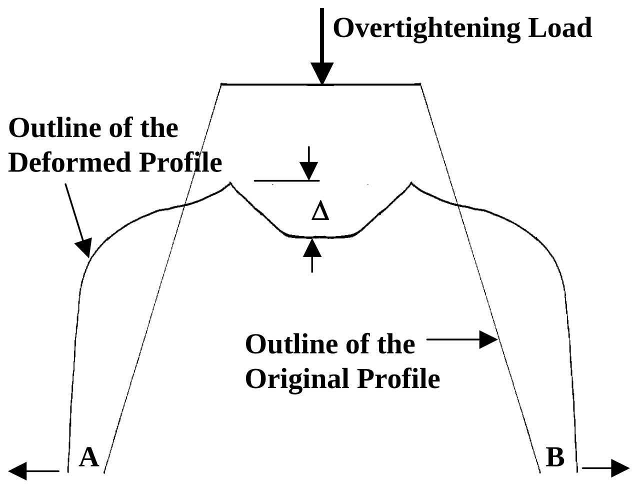
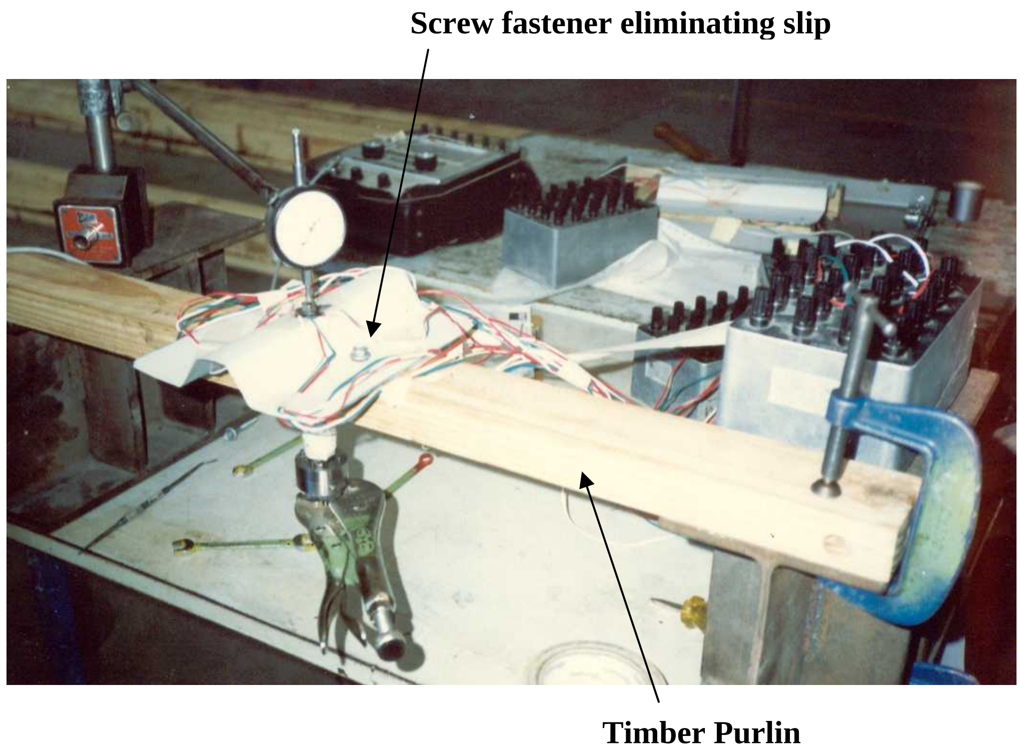
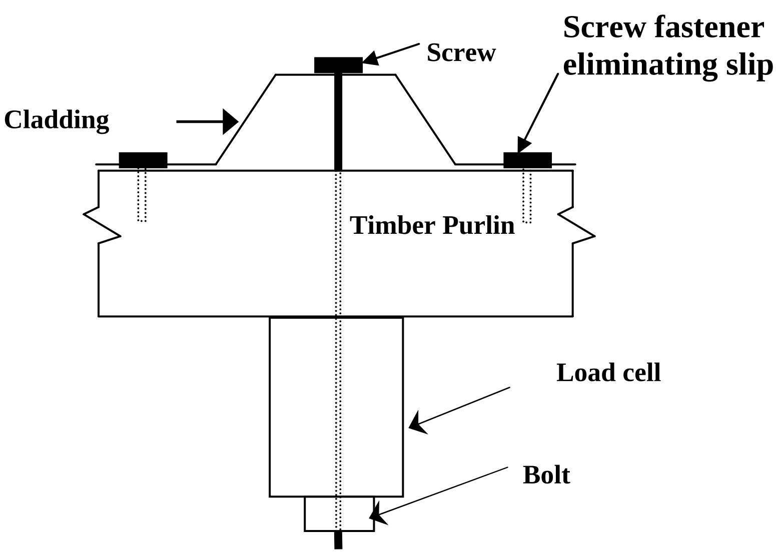


Figure 5. Deformed Geometry of Trapezoidal profile



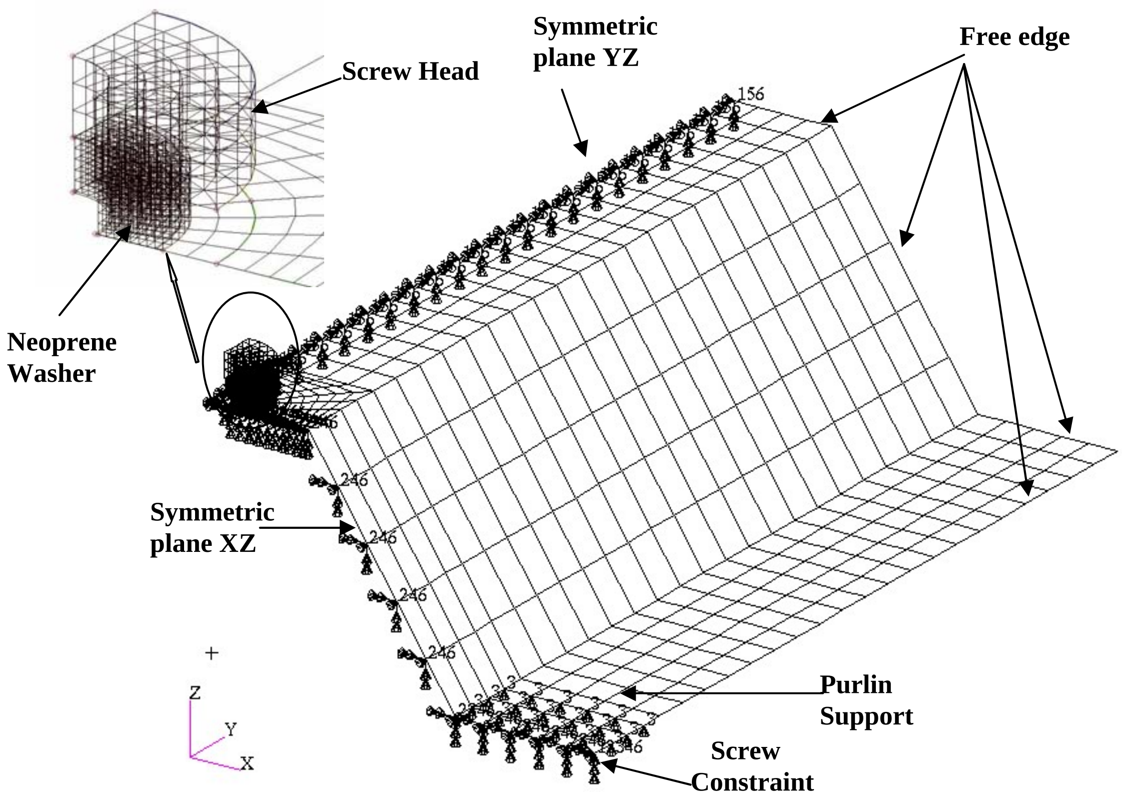
(a) Test Set-up



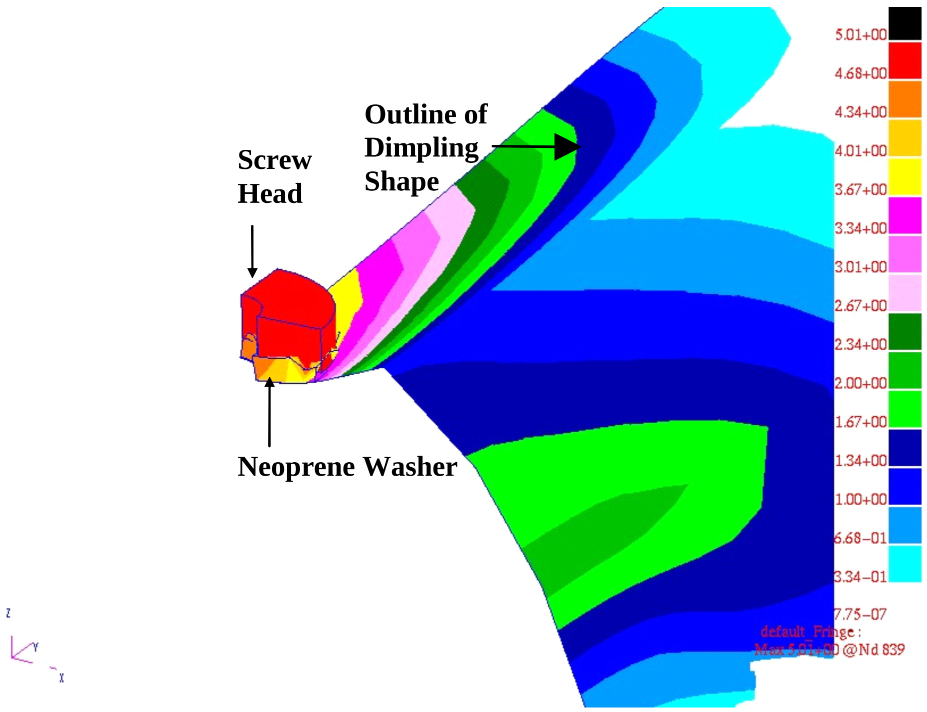
(b) Load Cell Arrangement

(c) Overtightening Method

Figure 6. Small Scale Test Model



(a) The Model used



(b) Deformed Sheeting (deformation contours in mm)

Figure 7. Finite Element Analysis

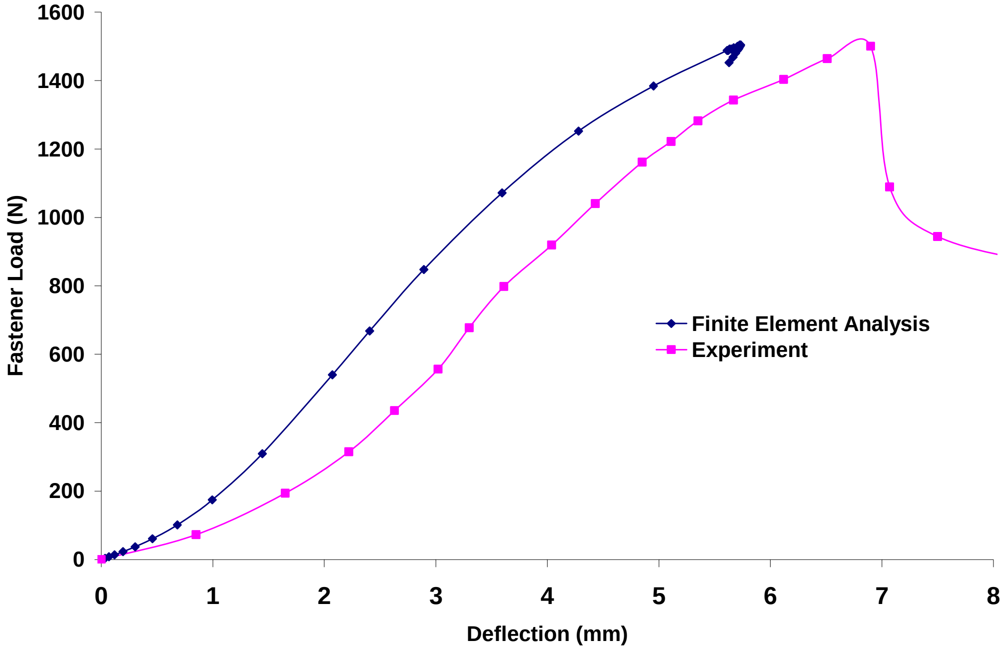


Figure 8. Load-deflection Curves for Trapezoidal-Type A Sheeting

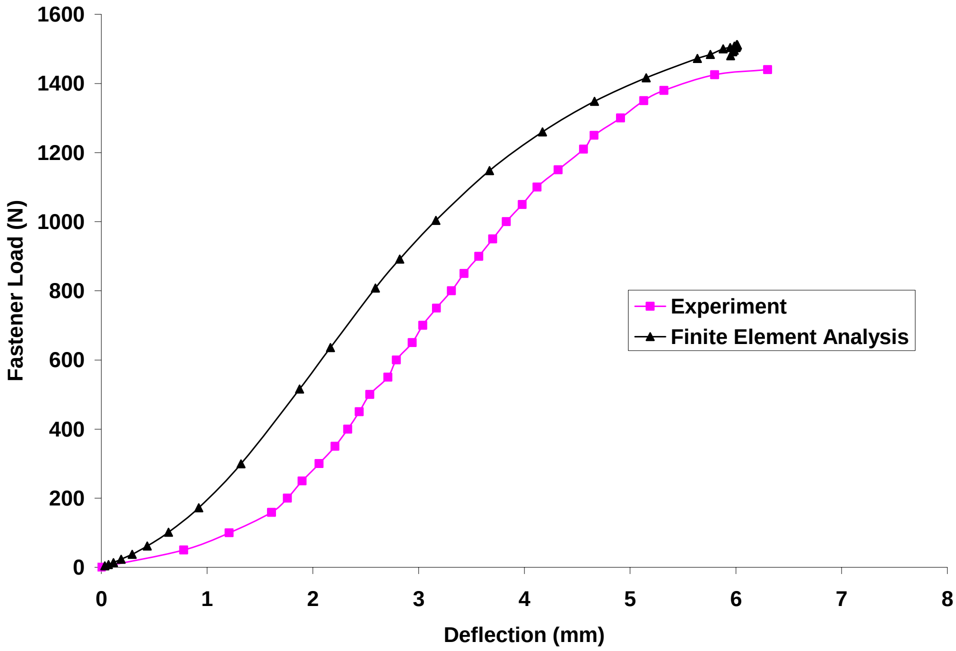


Figure 9. Load-deflection Curves for Trapezoidal-Type B Sheeting

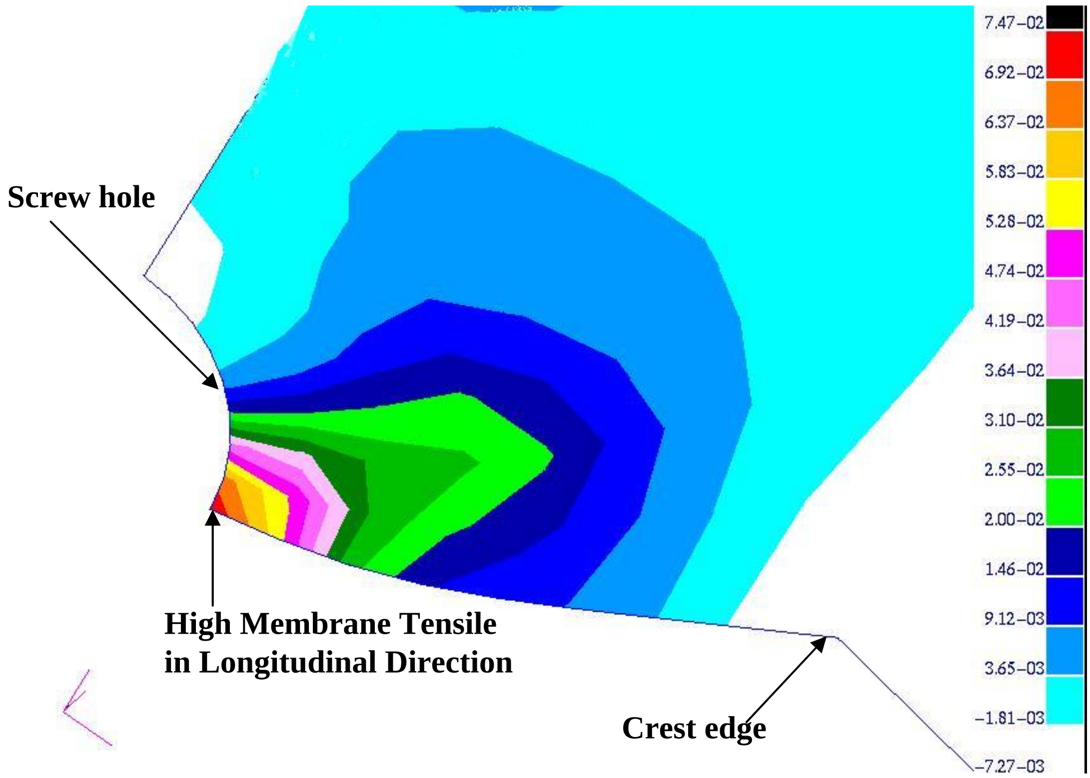


Figure 10. Membrane Strain Contours at the Fastener Hole

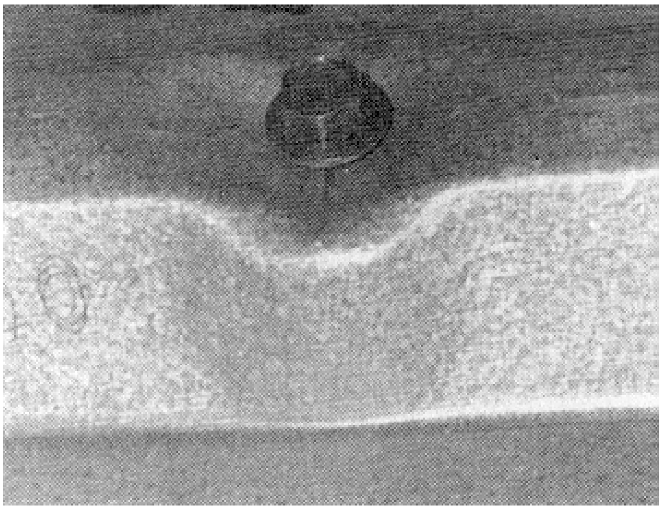


Figure 11. Local Dimpling Failure of Sheeting